

The anomaly in the cosmic-ray positron spectrum

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Abstract. A recent analysis of cosmic-ray data from a space borne experiment by the AMS collaboration supports the observation of an excess in the cosmic-ray positron spectrum by previous balloon experiments. The combination of the various experimental data establishes a deviation from the expected background with a significance of more than four standard deviations. The observed change in the spectral index cannot be explained without introducing a new source of positrons. When interpreted within the MSSM a consistent description of the antiproton spectrum, the diffuse gamma-ray flux and the positron fraction is obtained which is compatible with all other experimental data, including recent WMAP data.

PACS. 98.70.Sa Cosmic rays – 95.35.+d Dark Matter – 11.30.Pb Supersymmetry

1 Introduction

Among the cosmic-ray species, antiparticles and diffuse γ -rays are of particular interest because they are produced secondarily in hadronic interactions of protons and nuclei with the interstellar medium at low rates. Their small abundance makes them a sensitive probe for the existence of additional – and possibly exotic – cosmic-ray sources which would be visible as an excess of particles above conventional expectations.

One of the most important unsolved questions in modern cosmology is the nature of dark matter. The most promising dark matter candidate is the weakly interacting lightest neutralino, χ_1^0 , predicted by supersymmetric extensions to the standard model of particle physics. The annihilation of neutralinos might constitute an additional primary source of particles with a unique spectral shape which would be determined by the parameters of supersymmetry, allowing to put constraints on new physics beyond the standard model.

A recent reanalysis of the data from the AMS-01 spectrometer [1] supports the observation of an excess of cosmic-ray positrons by the HEAT experiments [2]. In this work, we discuss the combined results on the cosmic-ray positron fraction $e^+/(e^+ + e^-)$. Assuming that dark matter is largely constituted by neutralinos, we determine the cosmic-ray preferred parameter space of the minimal supersymmetric standard model (MSSM) from a simultaneous fit to the cosmic-ray positron, antiproton and diffuse γ -ray data.

ticle spectra as observed near Earth. GALPROP solves the propagation equation in a diffusion model with a given source distribution for all cosmic-ray species and includes convection, diffuse reacceleration, energy loss, fragmentation and decay in the interstellar medium. The injection spectra of nuclei and electrons before propagation are assumed to be power laws in momentum, and their spectral indices, γ_s and γ_e , respectively, are chosen such that the model reproduces the most recent cosmic-ray flux measurements.

From fitting the propagation model to electron and proton flux data we find the most probable values of these indices to be $\gamma_s = 2.35 \pm 0.03$ and $\gamma_e = 2.50 \pm 0.04$. In order to determine their errors and thus estimate the uncertainties of the model predictions, the indices have been varied over small intervals around their most probable values and the resulting predicted fluxes have been compared to the data. The χ^2 calculated from the deviation of the data from the respective prediction gives the 1σ errors of the injection spectral indices.

Fig. 1 shows the calculated fluxes of electrons and protons which are in excellent agreement with the experimental data over large energy intervals. The uncertainties of the propagation model – the fluxes calculated with the injection indices at their error limits – are denoted by the yellow areas. Below energies of several GeV, the individual measurements differ from each other due to the time-dependent effect of solar modulation.

2 Cosmic-ray particle propagation

The public GALPROP code [3] has been used to model cosmic-ray particle propagation and calculate the par-

3 The cosmic-ray positron fraction

The challenge of cosmic-ray positron measurements is the rejection of the vast proton background. A number of balloon borne experiments have delivered positron

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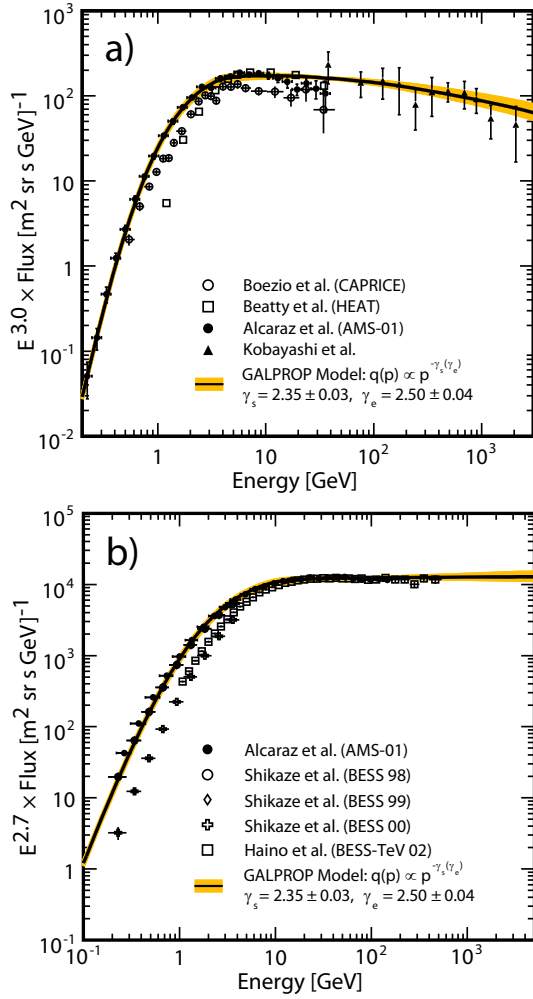


Fig. 1. a) Compilation of cosmic-ray electron flux data from CAPRICE [4], HEAT- e^\pm [2], AMS-01 [5] and Kobayashi et al. [6]. b) Proton flux data from AMS-01 [7] and BESS [8,9]. In both panels, the solid line denotes our GALPROP model and its uncertainty.

flux data in the energy range from 0.5 to 50 GeV, such as HEAT- e^\pm and HEAT-pbar [2], CAPRICE [4] and TS93 [10]. Additionally, the AMS-01 spectrometer has measured the positron flux up to 3 GeV [11] in a low Earth orbit. In order to extend the sensitivity of AMS-01 to energies of up to 50 GeV, a reanalysis of the data has been conducted [1] using the conversion of bremsstrahlung photons from positrons to achieve a proton background suppression of more than 10^5 . The result is shown in panel a) of Fig. 2 together with previous data.

In order to simplify data handling, the measurements on the positron fraction displayed in Fig. 2 a) have been combined into one single data set with regard to asymmetric statistical and systematic errors. Details of this procedure as well as a result table are given in Ref. [12]. Panel b) of Fig. 2 shows the combined data together with the model prediction. Above energies of 6 GeV, the data exhibit a change in the spectral index of positrons which is clearly incompati-

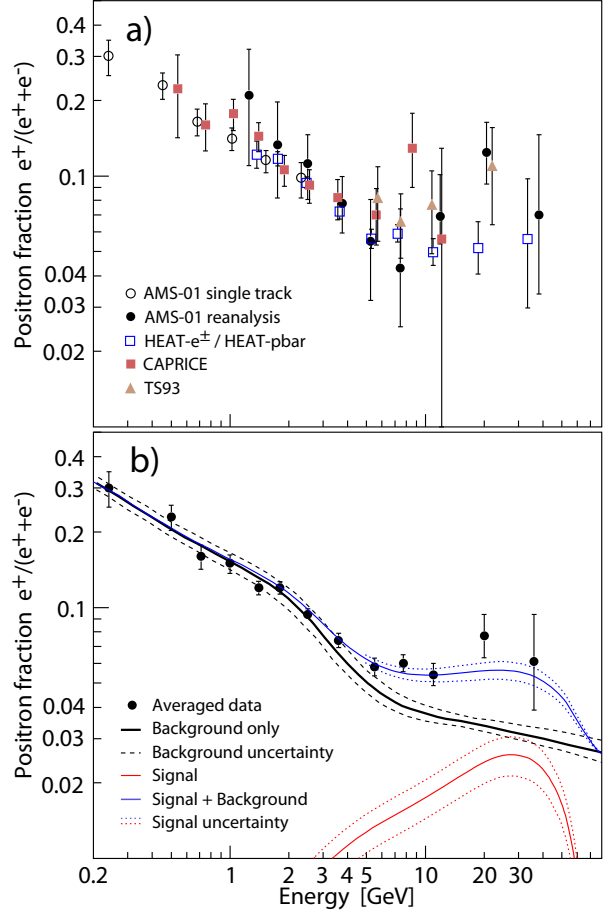


Fig. 2. a) Compilation of recent cosmic-ray positron fraction data from: AMS-01 (2000) [11], the AMS-01 reanalysis [1], HEAT- e^\pm and HEAT-pbar [2], CAPRICE [4] and TS93 [10]. b) The combined data together with the background model (thick solid line) and its uncertainty (dashed lines) as well as the neutralino annihilation signal and signal+background for the best fit parameter set (thin solid lines). The dotted lines denote the propagation uncertainties of the signal contribution.

ble with the expectation for purely secondary positron production. Taking into account experimental errors as well as the model uncertainty, the significance of the deviation amounts to more than four standard deviations. There is no set of propagation parameters based on which the GALPROP model would match the data satisfactorily. Consequently, the excess in the positron flux cannot be explained by the current propagation models and thus requires a new primary source of positrons.

4 The spectra of cosmic-ray antiprotons and diffuse γ -rays

Using the same procedure as stated in § 3, measurements of the cosmic-ray antiproton flux from AMS-01 [13], BESS97 [14], BESS00 [15] and CAPRICE [16] have been combined into one single data set. The result is displayed in panel a) of Fig. 3 together with

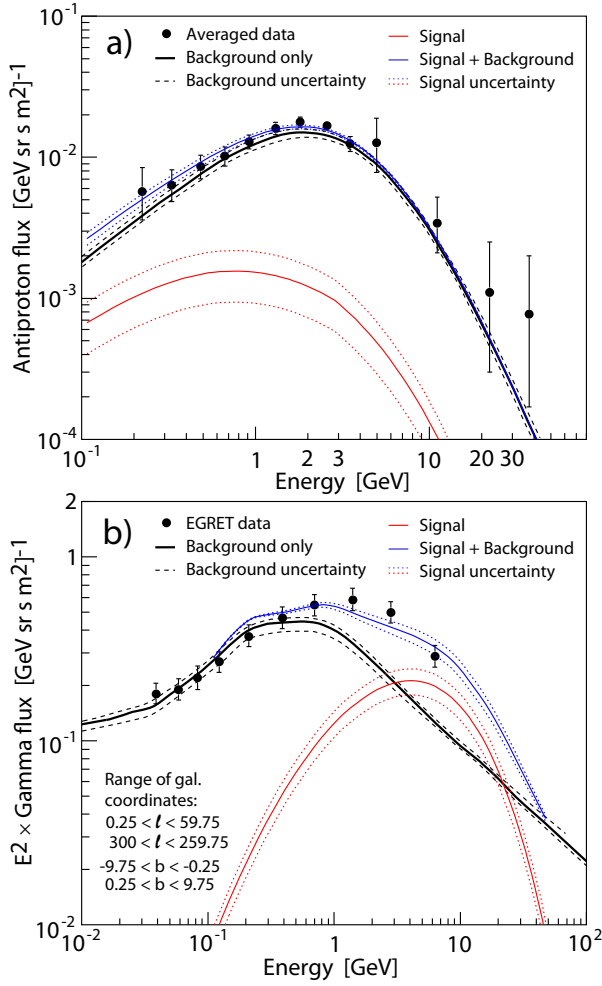


Fig. 3. a) The combined antiproton flux data. b) The diffuse γ -ray flux data from EGRET [17,18]. Both panels: modeled background (thick solid line) and its uncertainty (dashed lines) as well as the neutralino annihilation signal and signal+background for the best fit parameter set (thin solid lines). The dotted lines denote the propagation uncertainties of the signal contribution.

the GALPROP calculation. Within the experimental errors, the combined data are well in agreement with the expectation for purely secondary antiproton production.

Fig. 3 b) shows the flux of diffuse γ -rays measured by the EGRET [17,18] experiment. Above energies of 1 GeV, the data exhibit a significant excess with respect to the model calculation for purely secondary production which has been interpreted as an additional primary source of γ -rays from neutralino annihilations [19]. However, the particular model was claimed to be in conflict with the observed antiproton spectrum [20]. It has recently been pointed out that the excess could also be an artifact from energy misalignment of the experiment [21]. The discrepancy is in principle resolvable by fine-tuning the propagation model parameters, which however results in predictions for other particle species' spectra which are incompatible with experimental data [22].

5 Interpretation of the cosmic-ray spectra within the MSSM

5.1 Constraints on the MSSM parameter space

Measurements of several quantities are used to constrain the parameter space of the MSSM, such as the dark matter relic density from WMAP [23] and the branching ratios of the rare decays $b \rightarrow s\gamma$ [24] or $B_S \rightarrow \mu\mu$ [25]. Additional constraints come from the LEP2 experiments as lower limits on the neutralino [26] and neutral Higgs boson masses [27]. Furthermore, measurements of the anomalous magnetic moment of the muon [28] suggest low values of the MSSM parameters m_0 and $m_{1/2}$. Fig. 4 shows the plane spanned by m_0 and $m_{1/2}$ for $\tan\beta = 40$, $A_0 = 0$ and $\text{sign}\mu = +1$ together with the respective 2σ limits derived from the above constraints.

5.2 MSSM parameter scan with cosmic-ray data

In order to put further constraints on the MSSM parameter space from cosmic-ray data, we have conducted scans of the plane spanned by the parameters m_0 and $m_{1/2}$ for particular fixed values of $\tan\beta$. For each of the sample points in the plane the contributions to the positron fraction and the antiproton and γ -ray spectra from neutralino annihilation after galactic propagation have been calculated and simultaneously fitted to the experimental data together with the GALPROP models for the purely secondary background components. For the calculations, an isothermal dark matter halo profile with a local density of $\rho_0 = 0.3 \text{ GeV}/\text{cm}^3$ has been assumed. They were performed using the public DarkSUSY 4.1 [29], FeynHiggs 1.2.2 [30] and ISAJET 7.75 [31] packages with the top-quark mass fixed to $m_{\text{top}} = 170.9 \text{ GeV}$, $A_0 = 0$ and $\text{sign}\mu = +1$.

The particle fluxes Φ_i as observed near Earth can be described by adding the calculated signal contributions, S_i , for the individual particle species i to the respective GALPROP background models, B_i , according to $\Phi_i = B_i + f_i \cdot S_i$. Here, the f_i denote individual boost factors to allow for a signal enhancement due to a possible clumpy nature of the dark matter distribution in the solar neighborhood. In this case, we expect the individual boost factors to differ significantly from each other due to the different travel paths of the particle species which are determined by their mean energy loss. In particular, the boost factor for the antiproton signal should be small with respect to the others, since the low synchrotron radiation level of heavy particles allows them to be measured almost independently from their production location in the galaxy. The boost factors were determined as free parameters in fits of the Φ_i to the experimental data described in §3 and §4.

Fig. 4 shows the combined χ^2 from the simultaneous fits as a function of m_0 and $m_{1/2}$ for $\tan\beta = 40$. Apparently, the cosmic-ray data clearly favor the focus point region at large values of m_0 , and we find the best fit parameters to be $m_0 = 1230 \text{ GeV}$ and

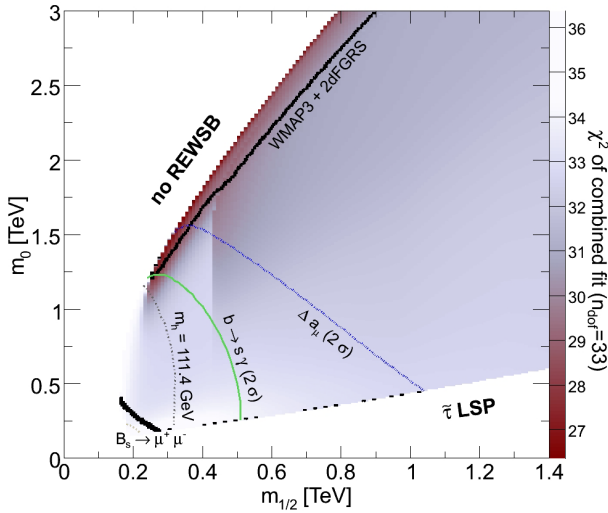


Fig. 4. The plane spanned by the MSSM parameters m_0 and $m_{1/2}$ for $\tan\beta = 40$, $A_0 = 0$ and $\text{sign}\mu = +1$. Current experimental constraints (2σ) are denoted by the solid, dotted and dash-dotted lines. The color scale gives the χ^2 of the MSSM fit to the cosmic-ray data.

$m_{1/2} = 260$ GeV. This point is well in agreement with all constraints on the MSSM parameter space stated in § 5.1, including recent data from WMAP.

The contributions from neutralino annihilation to the individual particle spectra as well as the signal + background curves for the best fit parameter set are shown in Fig. 2 b) and 3 in comparison with the experimental data. With the additional primary cosmic-ray component from neutralino annihilation, the experimental data for the positron fraction and the spectra of antiprotons and γ -rays can well be reproduced. The combined χ^2 turns out to be 28 with 33 degrees of freedom, and the boost factors f_i are found to be 85 ± 15 for positrons, 1 ± 0.5 in the case of antiprotons and 310 ± 50 for γ -rays.

In the region of the parameter space preferred by the cosmic-ray data, neutralinos have a significant higgsino component of more than 30% and dominantly annihilate into W-boson pairs via t-channel exchange of charginos. For the best fit parameters, we find the mass of the χ_1^0 to be 91 GeV and a value for the mass of the lightest Higgs boson of 113.7 GeV.

5.3 Dependence on $\tan\beta$ and m_{top}

The choice of $\tan\beta$ is critical to constrain the MSSM parameter space with cosmic-ray data. For varying values of $\tan\beta$, the combined fits favor a neutralino mass between 80 GeV and 120 GeV. Unless $\tan\beta$ is higher than 50, we always find an overlap of the parameter space favored by cosmic rays with the relic density constraints from WMAP in the focus point region. Furthermore, the preference of cosmic rays in terms of the MSSM parameter space is sensitive to the mass of the top-quark, whose value is currently known with a precision of 1.8 GeV[32]. In particular, for low $\tan\beta$ and

values of $m_{\text{top}} > 173$ GeV, the focus point region is not available unless m_0 is larger than about 3 TeV. In order to put accurate constraints on the MSSM parameter space from cosmic-ray data, the impact of varying values of $\tan\beta$ and m_{top} has to be investigated further.

6 Conclusions

In this work, the combined recent experimental results on the cosmic-ray positron fraction have been presented. The data exhibit an excess of positrons above energies of 6 GeV which cannot be explained by purely secondary positron production alone and thus requires an additional primary source of positrons. In this work, we interpret this source to be the annihilation of supersymmetric neutralinos constituting dark matter. A simultaneous fit to the cosmic-ray positron, antiproton and γ -ray data shows that, for particular sets of the MSSM parameters, this hypothesis gives a fully consistent description of the cosmic-ray spectra which is compatible with all other experimental data. We find that the cosmic-ray data clearly prefer the focus point region of the MSSM parameter space but reveal almost no sensitivity to $\tan\beta$.

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